Reply

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In their previous paper, Stammer and Böning (1992, hereafter SB) investigated the characteristics of the mesoscale variability in the Atlantic Ocean using Geosat altimeter data. Wavenumber spectra and spatial eddy characteristics were analyzed in various subdomains of 10° by 10° geographical extent, covering both hemispheres of the Atlantic Ocean. In several earlier studies on spatial scales and wavenumber spectra of oceanic mesoscale variability based on Seasat and Geosat altimeter data, pronounced differences in spectral slopes were typically associated with areas of higher and lower eddy energy (Fu 1983; Fu and Zlotnicki 1989, hereafter FZ; LeTraon et al. 1990, hereafter LRB). In all of these earlier studies, differences in spectral slopes were interpreted as a manifestation of different dynamical regimes in the ocean; however, SB offered an alternative interpretation by taking into account uncertainties due to analysis procedures and data errors (instrumental noise and residual environmental and orbit error) and by considering results from high-resolution numerical modeling. They suggested two possible reasons for the weak spectral slopes that apparently characterize altimeter data in low-energy areas:

(i) the large extent of the analyzed arc segments, as in Fu and FZ, which due to a substantial meridional variation of eddy scales, leads to smoothed spectra with significantly reduced slopes (cf. SB, Fig. 7);

(ii) and, relevant to LRB and SB, a contaminating effect of measurement noise and other types of errors such as residual environmental errors.

In principle, this does not rule out the possibility of different types of wavenumber spectra in the ocean. But as stated by SB in their conclusions, there is "no conclusive evidence of a significant departure from k^{-4} to k^{-5} type spectra" in the presently available altimeter data. Instead, there are indications that spectral slopes roughly corresponding to a k^{-3} power law of geostrophic turbulence may represent a universal characteristic of the ocean eddy field. These conclusions have been questioned by LeTraon (1993, hereafter LT). By summarizing the results from LRB, the author hints at geographical variations of spectral characteristics, which seemingly contradict some of the conclusions given by SB.

We feel that it is mandatory to give a thorough discussion of data uncertainties while interpreting results from Geosat data in terms of ocean dynamics. It is generally accepted that Geosat data are subject to a variety of error sources with diverse frequency–wavenumber characteristics and that the overall error level of Geosat data due to both instrumental noise and residual environmental and orbit errors is of the order of several centimeters. Even though comparative studies reveal a reasonable (not very good as stated in LT!) representation of observed eddy signals even in low-energy areas (e.g., see Stammer et al. 1991), those results are basically restricted to a limited wavenumber band roughly corresponding to scales between 100 and 500 km. As noted in all previous studies, the instrumental noise dominates at high wavenumbers, where it leads to a "white" part of the spectrum. Concerning residual environmental errors, it has been discussed previously (e.g., Fu 1983; LRB) that those from water vapor corrections and inverse barometer effects are the most critical terms. Although mesoscale spectra from high-energy regions are considered to be only slightly affected by those errors on wavelengths smaller than 1000 km, their impact on altimeter residuals is likely to increase for low-energy areas at wavelengths of 500 km or longer (Fu 1983), thus leading to spectra that, at those long wavelengths, resemble characteristics of the error sources with slopes of about k^{-2} as shown, for example, in LRB (their Fig. 9). Due to the error sources at both high and low wavenumbers, an interpretation of such spectra from low energy areas has to be limited to a narrow intermediate wavenumber band. To illustrate the uncertainty of spectra from low-energy regions, Fig. 1 shows wavenumber spectra from 10° by 10° areas along 35°N redrawn from LRB (Fig. 1a) and SB (Fig. 1b), which characterize both high- and low-energy regions. As compared to the energetic western basin, in the low-energy areas east of 30°W the noise-dominated part of the spectra at high wavenum-

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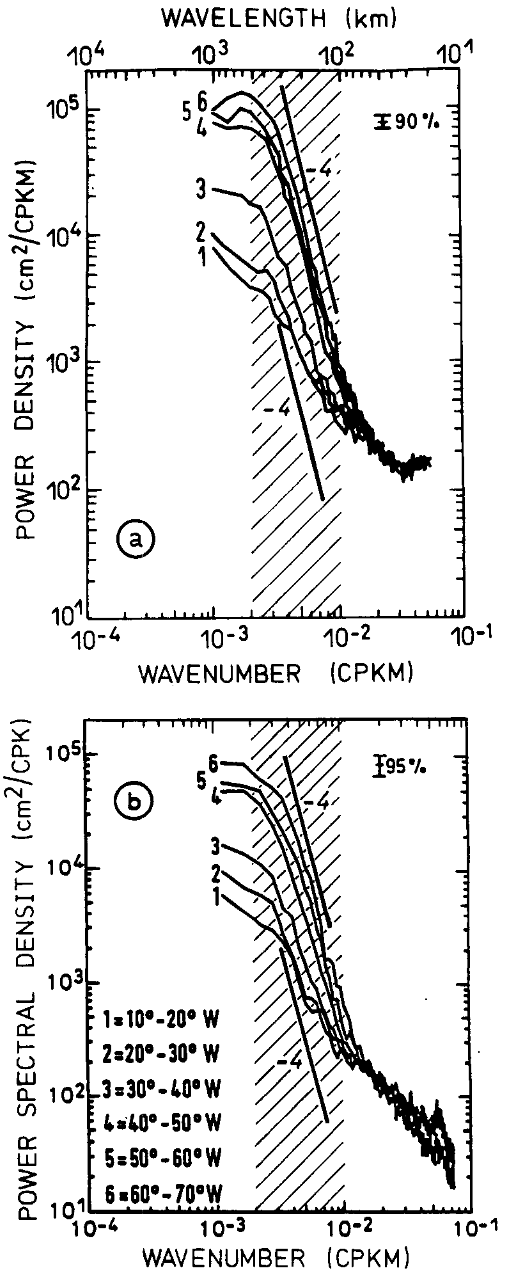

FIG. 1. Geosat mean alongtrack wavenumber spectra of sea surface height anomalies in 10° by 10° areas along 35°N in the North Atlantic Ocean (a) as given by Le Traon et al. (1990) from both ascending and descending tracks and (b) given by Stammer and Böning (1992) from ascending tracks only. For labeling of both panels see (b). Shading has been added to indicate that part of the spectrum that presumably is not degraded by instrumental noise or long wavelengths environmental error sources.

bers obviously extend to lower wavenumbers. It is also in those latter curves that a deviation from a plateau at long wavelengths can be found. This tendency toward "red" spectra at long wavelength, which LT attributes to an effect of wind-induced eddy activity, is a peculiarity of all low-energy subdomains in which the energy level at long wavelengths falls below 10^4 $cm^2/cpkm$; that is, where the altimeter spectrum approaches the level of the error spectrum. It is even more enhanced in those areas of the tropics and subtropics where the energy level is a minimum and where k^{-2} type spectra are found over the full wavenumber range. It is essential to note, however, that despite those uncertainties, a clear break in the spectral slope can be found in many of those critical areas on a narrow wavenumber band with a tendency to k^{-4} relations much like in those areas with higher eddy energy (cf. Fig. 1b).

Although principally similar, the results of LRB (based on data from both ascending and descending tracks) are different to those of SB (from ascending tracks only, due to the data uncertainty in descending tracks at the western and eastern side of the basin), especially in the critical areas east of 30°W (area number 1 and 2 in Fig. 1). There the much smoother spectra from LRB somewhat obscure the uniform spectral relation on scales between 100 and 500 km, as presented in Fig. 1b. Such differences have to be attributed to details of the analysis procedure like the collinear analysis, blunder point detection, filtering, and others and imply a further complication in the interpretation of wavenumber spectra. (Note, e.g., that in contrast to SB no inverse barometer correction has been applied by LRB.) To illustrate this uncertainty, Fig. 2 shows two wavenumber spectra separately from ascending and descending tracks for the area 40°–50°N, 10°–20°W (i.e., adjacent north to area 1 in Fig. 1). Differences between the two curves may be due to residual data errors or due to an anisotropy of the oceanic eddy field and reveal the effective uncertainty of the spectra, which can exceed the statistical estimation errors given in LRB by more than a factor of three.

LRG and LT allege that the noise-induced error does not affect the spectra for wavelengths longer than about 50–100 km. They likewise argue that spectra from all 10° by 10° areas north of 20°N are not contaminated by erroneous environmental corrections or other systematic error sources on smaller wavenumbers. We believe that the extent to which spectral shapes in the mesoscale range are contaminated cannot be judged by inspection of the spectra alone. It is obvious that the effect must be different in regions with different signal-to-noise ratios. Stammer and Böning (1992) have demonstrated that the rms signal in the high-frequency band (i.e., with periods less than 6 months) did not exceed 4–5 cm in those 10° by 10° areas of the Atlantic that exhibited spectral slopes as weak as k^{-2}. They also noted corroborative indications for a degrading effect of measurement noise in the structure of the autocorrelation function. The vague assertion of LT that mesoscale spectra in these regions are only slightly affected by error sources appears rather optimistic.

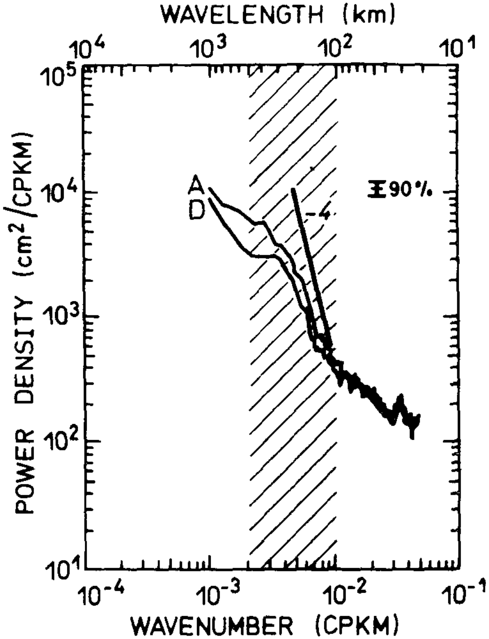

FIG. 2. Geosat mean alongtrack wavenumber spectra of sea surface height anomalies in the area 40°–50°N, 10°–20°W. Shown are results separately from (A) ascending and (D) descending tracks (after Le Traon et al. 1990).

Without a firm observational basis for oceanic wavenumber spectra with slopes corresponding to a white or blue energy spectrum, a search for possible dynamical factors for such behavior appears somewhat premature. Nonetheless, none of the processes cited by LRB and LT would readily explain a tendency to white or even blue wavenumber spectra in low-energy regions of the ocean. We think that a well-founded assessment of oceanic wavenumber spectra for regions with weak mesoscale activity can be given only when new altimeter data with significantly reduced error levels become available. Fortunately, those high-quality data are expected from the most recent TOPEX/*Poseidon* mission. On the basis of this new dataset, it should be possible to give a more precise discussion of mesoscale characteristics like wavenumber spectra and eddy scales and to start a consolidated discussion about ocean dynamics including areas with low eddy variability. At present, however, there is no solid observational evidence that would contradict the conclusions drawn by SB from a thorough analysis of Geosat data from the entire Atlantic Ocean.

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